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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The objective of this research effort has been to develop algorithms for in situ location and identification, by ultrasound, of flaws in plates or laminated layered elastic materials. Achieving this objective requires detailed knowledge of the excitation, propagation, scattering and detection of high frequency sound waves in the unflawed and flawed environments. Based on an understanding of these fundamental wave phenomena, one may then attempt to construct analytical models with accompanying algorithms, so as to parametrize the NDE problem in terms of "good observables".

During the contract period, carefully selected prototype problems have been investigated to determine "good observables" for particular flawed environments. Two major phases have received attention: (a) phenomena within a flat layered plate, especially beam-to-mode conversion, and the consequent interaction with a weak debonding flaw; (b) characterization of transducer outputs in terms of "good" wave objects that facilitate coupling into and out of,

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19 Abstract (continued)

the plate environment. The analytical tools rely on spatial and spectral domain formulations, and they comprise self-consistent hybrid beam-mode methods; complex source modeling of Gaussian beams, with complex ray tracing to track such beams; and decomposition of general wavefields into Gaussian beams. Thus, Gaussian beams, which are "good observables" are central to the problem strategy.

Specific accomplishments during the contract period include construction of analytical models and their numerical implementation for the following problems in category (a): (i) detailed understanding of the beam-to-mode conversion mechanism in an unflawed elastic plate, and the observable displacements generated thereby on the plate surface; (ii) surface displacements generated due to interaction of the waves in (i) with a localized smoothly tapered weak debond zone: (iii) beam-observable-based parametrization of the results in (i) and (ii), and construction of a beam algorithm for compact forward and inverse analysis of the scattered data. In category (b), model outputs from a piston-type transducer in an unbounded elastic medium have been decomposed rigorously into Gaussian basis beams. For future applications, these building blocks should facilitate the systematic study of transducer excited plates, generalization to c''rved plates, etc., in terms of robust algorithms that are closely linked with what is actu- / observed.

18 Subject Terms (continued)

NDE in layered plates

IN SITU FAULT DETECTION BY THE HYBRID RAY MODE METHOD

Final Report

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Table of Contents

Abstract

The objective of this research effort has been to develop algorithms for *in situ* location and identification, by ultrasound, of flaws in plates or laminated layered elastic materials. Achieving this objective requires detailed knowledge of the excitation, propagation, scattering and detection of high frequency sound waves in the unflawed and flawed environments. Based on an understanding of these fundamental wave phenomena, one may then attempt to construct analytical models with accompanying algorithms, so as to parametrize the NDE problem in terms of "good observables."

During the contract period, carefully selected prototype problems have been investigated to determine "good observables" for particular flawed environments. Two major phases have received attention: a) phenomena within a flat layered plate, especially beam-to-mode conversion, and the consequent interaction with a weak debonding flaw; b) characterization of transducer outputs in terms of "good" wave objects that facilitate coupling into and out of the plate environment. The analytical tools rely on spatial and spectral domain formulations and they comprise self-consistent hybrid beam-mode methods; complex source modeling of Gaussian beams, with complex ray tracing to track such beams; and decomposition of general wavefields into Gaussian beams. Thus, Gaussian beams, which are "good observables", are central to the problem strategy. Specific accomplishments during the contract period include construction of analytical models and their numerical implementation for the following problems in category a): (i) detailed understanding of the beam-to-mode conversion mechanism in an unflawed elastic plate, and the observable displacements generated thereby on the plate surface; (ii) surface displacements generated due to interaction of the waves in (i) with a localized smoothly tapered weak debond zone; (iii) beam-observable-based parametrization of the results in (i) and (ii), and construction of a beam algorithm for compact forward and inverse analysis of the scattered data. In category b), model outputs from a piston-type transducer in an unbounded elastic medium have been decomposed rigorously into Gaussian basis beams. For future applications, these building blocks should facilitate the systematic study of transducer excited plates, generalization to curved plates, etc., in terms of robust algorithms that are closely linked with what is actually observed.

I. Background

The objective of this research effort has been to develop algorithms for *in situ* location and identification, by ultrasound, of flaws in plates or laminated layered elastic materials. Achieving this objective requires detailed knowledge of the excitation, propagation, scattering and detection of high frequency sound waves in the unflawed and flawed environments. Based on an understanding of these fundamental wave phenomena, one may then attempt to construct analytical models with accompanying algorithms, so as to parametrize the NDE problem in terms of "good observables."

During the contract period, carefully selected prototype problems have been investigated to determine "good observables" for particular flawed environments. Two major phases have received attention:

a) phenomena within a flat layered plate, especially beam-to-mode conversion, and the consequent interaction with a weak debonding flaw

b) characterization of transducer outputs in terms of "good" wave objects that facilitate coupling into and out of the plate environment

The analytical tools rely on spatial and spectral domain formulations, and they comprise self-consistent hybrid beam-mode methods; complex source modeling of Gaussian beams, with complex ray tracing to track such beams; and decomposition of general wavefields into Gaussian beams. Thus, Gaussian beams, which are "good observables", are central to the problem strategy.

Specific accomplishments during the contract period include construction of analytical models and their numerical implementation for the following problems in category a):

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(ii) surface displacements generated due to interaction of the waves in (i) with a localized smoothly tapered weak debond zone

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In category b), model outputs from a piston-type transducer in an unbounded elastic medium have been decomposed rigorously into Gaussian basis beams. For future applications, these building blocks should facilitate the systematic study of transducer excited plates, generalization to curved plates, etc., in terms of robust algorithms that are closely linked with what is actually observed.

The problem strategy is summarized in Figs. 1a, b.

II. Summary of Results

In what follows, the cited publications are those listed in Section III. Copies of the manuscripts have previously been furnished to the sponsor.

A. Modeling of Wave Phenomena within a Bonded Two-Layer Aluminum Plate in Vacuum (Two-Dimensional)

1. Gaussian P-beam excitation of the unflawed (perfectly bonded) plate

This study was performed to clarify in detail the beam-to-mode conversion when an obliquely injected high-frequency compressional (P) beam excites the plate. The Gaussian beam has been modeled by the complex-source-point (CSP) method, and the elastic potentials and displacements in the interior and on the surface of the plate have been computed via P-SV-coupled normal mode expansion (SV denotes vertically polarized shear) [1-3]. The results from this reference calculation have been analyzed and subjected to various spatial and spectral filterings to establish "good" signal processing [4]. It was observed that the field initially has beam-like features, thereby suggesting that the mode algorithm does not furnish a good parametrization in that regime.

Some of these results are schematized in Figs. 2 and 3.

2. Scattering from a weak, smoothly varying, localized debond for the problem in 1: normal mode reference solution

The debond, which is sensitive to horizontal shear along the bond line but not to compressional waves, was modeled by springs with Gaussian stiffness profile. The equivalent sources induced in the debond zone were treated in the Born approximation (i.e., proportional to the field at the bond line in absence of the flaw) because of the "weak debond" assumption. The scattered fields have been computed via the normal mode algorithm, with excitation terms provided by the induced source distribution. In the beam-like regime of Fig. 3, the observed displacements on the upper surface reveal a clearly identifiable flaw-generated beam-like precursor [5,6] which suggests that an observable-based efficient algorithm should be based on beam rather than mode decomposition.

Some of the results are shown in Fig. 4.

3. Observable-based beam parametrization of the problem in 2.

Because the reference data in 2. clearly establish beams as the physical observables (see Fig. 4), the problem has been re-parametrized in terms of beams. Algorithms have been developed for simple construction and interpretation of the displacements on the surface of the plate generated under unflawed and flawed conditions, and for the reconstruction of the input beam source and the flaw characteristics from the on-surface data [7].

Some results are schematized in Figs. 5a, b.

4. General conclusion

The beam parametrization in 3. furnishes a promising algorithm for detecting, locating, and identifying the strength of smoothly variable weak debonds of moderate extent.

B. Modeling of Transducer Outputs in Terms of Gaussian Beams

While some ultrasonic transducers generate outputs that resemble Gaussian beams (GB), this is not the case in general. It is desirable to decompose arbitrary outputs into Gaussians because GB basis fields have favorable propagation characteristics under rather general environmental conditions. The study was initiated in two dimensions, and it expresses an arbitrary source field in an infinite elastic medium *rigorously* in terms of Gaussian elements spaced self-consistently on a (configuration)-(spectral wavenumber) lattice. The physical behavior of the resulting field representation, as well as its convergence properties, depend strongly on the choice of wide, narrow or "matched" beam elements. These aspects have been investigated in detail for smooth and abruptly truncated source profiles that simulate transducer outputs [8,9]. The extension to three dimensions has been performed thereafter [10].

Some results are shown in Fig. 6a, b. A future phase would couple these basis beams to the plate environment, either directly from the surface or, when the plate is immersed, from a transducer in the fluid through the fluid-plate interface.

III. Publications

1. I.T. Lu, L.B. Felsen and J.M. Klosner, "Beam-to-Mode Conversion of a High Frequency Gaussian P-Wave Input in an Elastic Plate Embedded in Vacuum," in *Review of Progress in Quantitative Non-destruction Evaluation,* ed. D.O. Thompson and D.E. Chimenti, Plenum Press, New York, 1987.

2. I.T. Lu, L.B. Felsen and J.M. Klosner, "Beam-to-Mode Conversion of a High Frequency Gaussian P-Wave Input in an Aluminum Plate in Vacuum," in ASME Symposium on New Directions in the Ultrasonic NDE of Advanced Materials (November 1988).

3. I.T. Lu, L.B. Felsen and J.M. Klosner, "Beam-to-Mode Conversion in an Aluminum Plate for Ultrasonic NDE Application," ASME Journal of Engineering Materials and Technology, Vol. 112, No. 2, April 1990, pp. 236-240.

4. I.T. Lu, L.B. Felsen and J.M. Klosner, "Observables due to Beam-to-Mode Conversion of a High Frequency Gaussian P-wave Input in an Aluminum Plate in Vaccum," J. Acoust. Soc. Amer. Vol. 87, No. 1, January 1990, pp.

42-53.

5. I.T. Lu, L.B. Felsen, J.M. Klosner and C. Gabay, "Beam and Mode Analysis of Weak Bonding Flaws in a Layered Aluminum Plate," in *Elastic Wave Propagation,* ed. M.F. McCarthy and M.A. Hayes, Elsevier, New York, 1989, 205-210.

6. I.T. Lu, L.B. Felsen, J.M. Klosner and C. Gabay, "Beams and Modes for Scattering from Weak Bonding Flaws in a Layered Aluminum Plate," J. Acoust. Soc. Amer., accepted for publication.

7. L.B. Felsen and S. Zeroug, "Beam Parametrization of Localized Weak Debonding in a Layered Aluminum Plate," in *Review of Progress in Quantitative Nondestructive Evaluation,* Vol. 9, ed. D.O. Thompson and D. Chimenti, Plenum Press, New York, 1990, pp. 195-202.

8. L.B. Felsen, J.M. Klosner, I.T. Lu and H. Grossfeld, "Source Field Modeling by Self-Consistent Gaussian Beam Superposition," in *Review of Progress in Quantitative Nondestructive Evaluation,* ed. D.O. Thompson and D. Chimenti, Plenum Press, New York, 1988.

9. L.B. Felsen, J.M. Klosner, I.T. Lu and H. Grossfeld, "Source Field Modeling by Self-Consistent Gaussian Beam Superposition (Two-Dimensional)," submitted to J. Acoust. Soc. Amer.

10. J.M. Klosner, L.B. Felsen, I.T. Lu and H. Grossfeld, "Three-Dimensional Gaussian Beam Superposition for Transducer Source Field Modeling," in preparation.

IV. Personnel

Dr. L.B. Felsen, University Professor, Principal Investigator.

Dr. J.M. Klosner, Professor, Dept. of Mechanical Engineering, Co-Principal Investigator.

C. Gabay, Ph.D. Candidate, Dept. of Mechanical Engineering.

H. Grossfeld, Ph.D. Candidate, Dept. of Mechanical Engineering.

S. Zeroug, Ph.D. Candidate, Dept. of Electrical Engineering.

Degrees granted:

1. C. Gabay, "Gaussian Beam Scattering by an Imperfect Bond in a Layered Elastic Plate," Ph.D. (Applied Mechanics), January 1989.

2. H. Grossfeld, "Source Field Modeling by Self-Consistent Gaussian Beam Superposition," Ph.D. (Stress Analysis), June 1989.

Problem Strategy

Constituent problems:

1. modeling of transducer input (primary sources)
2. propagation of excited fields into layered environment
3. interaction with fault zones (equivalent secondary sources)
4. propagation of scattered (secondary source) fields to receiver
5. detection and interpretation of total signal

In each problem category: use algorithm with good parametrization

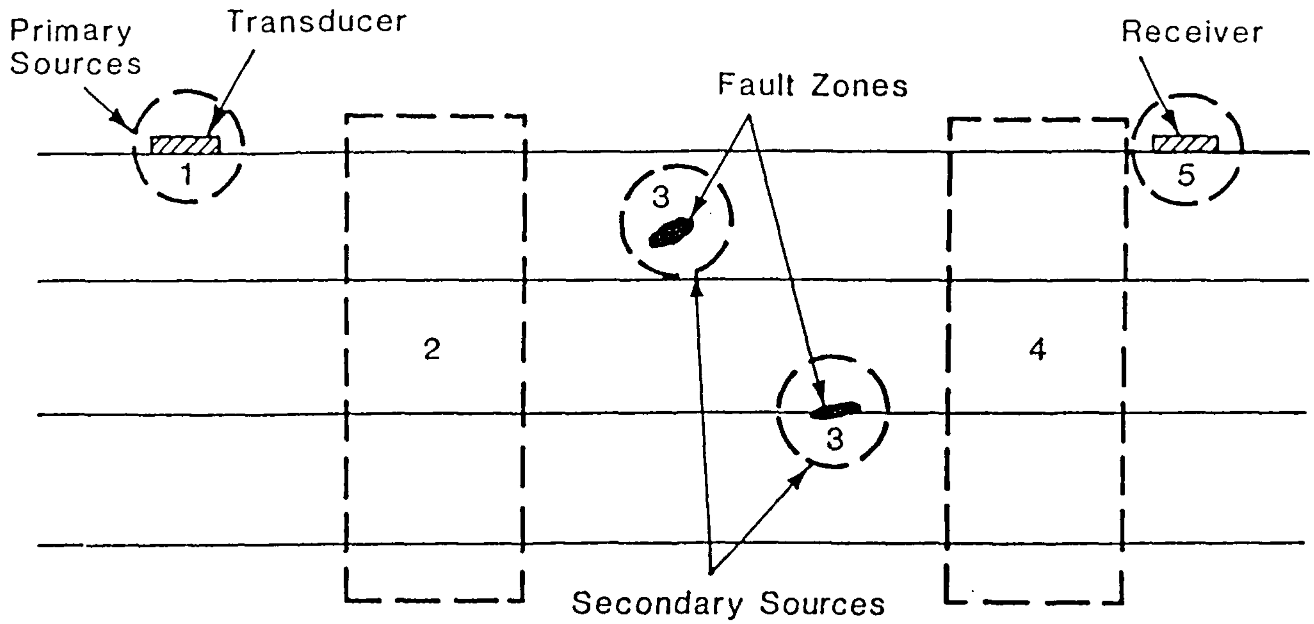


Fig. 1a

Objective of the Research

** To develop algorithms for ultrasound in-situ detection and identification of fault zones in layered media in terms of <u>good observables</u> $\Longrightarrow$ <u>good parametrization.</u>

** <u>Good observables</u> (either steady-state or transient) are closely tied to the physics of wave phenomena.

** Wave phenomena: dilatational, shear, anisotropic species, etc.

** Examples of good observables in layered media:

. rays

. beams

. guided modes (trapped, leaky, interfacial)

** Most versatile <u>parametrization</u>: $\left\{\begin{matrix}\text{ray}\\ \text{beam}\end{matrix}\right\}$ - mode algorithm

. Combines $\left\{\begin{matrix}\text{rays}\\ \text{beams}\end{matrix}\right\}$ and modes <u>self-consistently,</u> utilizing the best features of each

. Robust under gradual changes from prototype models

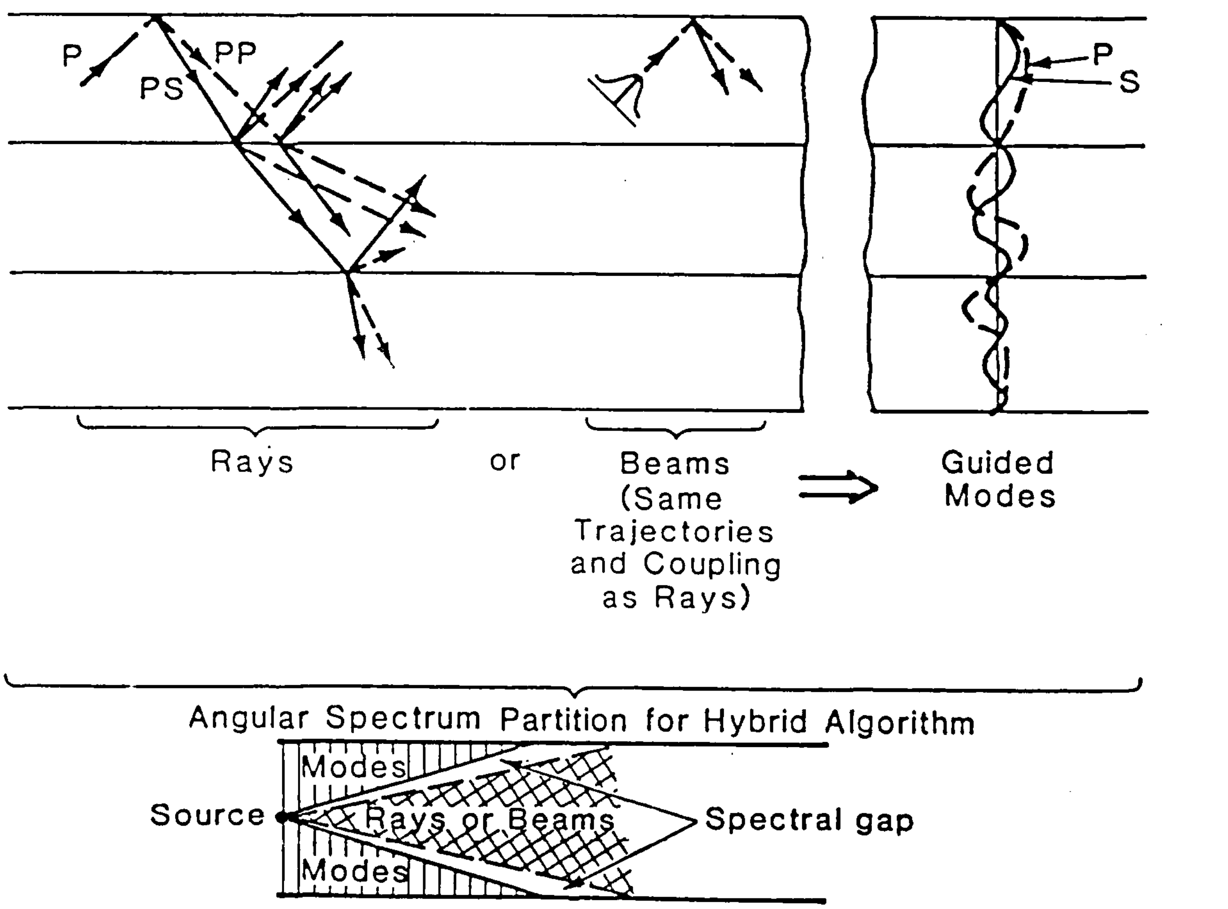
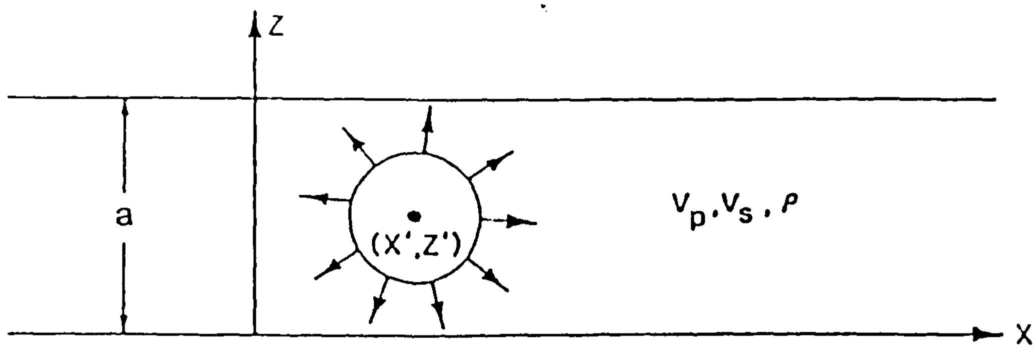
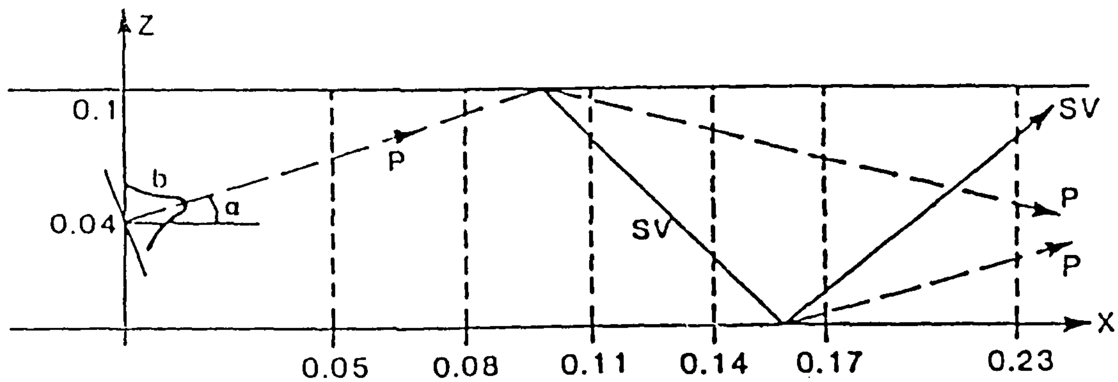


Fig. 1b



(a) real source coordinates (x', z') (P-wave isotropic line source).



(b) complex source coordinates $(\tilde{x}', \tilde{z}')$ (P-wave beam source). The beam parameter b is related to the (1/e) beam width w_e at the waist, $w_e=(2b/k_p)^{1/2}$. Also shown on this figure are the axes of the incident and reflected P-beams (dashed lines), and of the coupled SV-beams (solid lines) and their relationship to the cross sections in Fig. 2.

Fig. 2 Elastic aluminum plate with thickness a, characterized by wave velocities v_p, v_s and by density ρ.

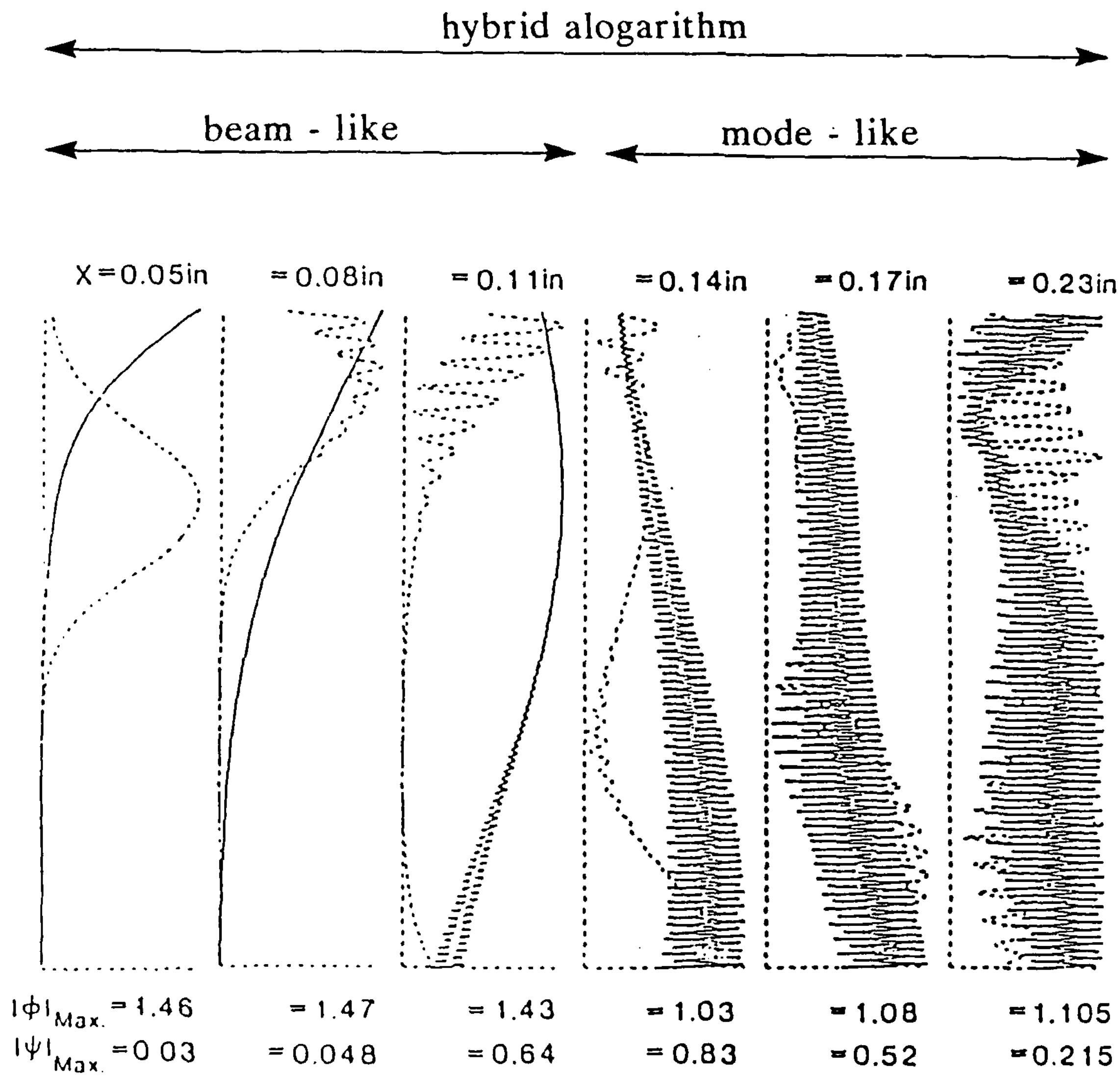
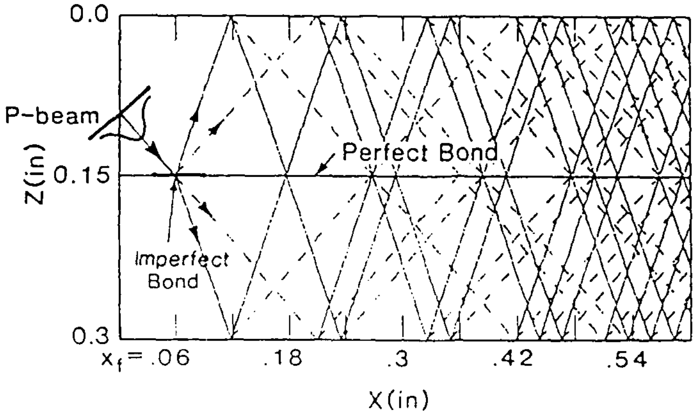


Fig. 3 Amplitude profiles of the P-wave potential Φ (dashed) and the SV-wave potential Ψ (solid) due to a P-beam input. observed at successive plate cross sections in the interval from x= 0.05 in. to x= 0.23 in. The frequency is 60 MHz. The beam parameters are: $x'=0$, $z'=0.04$ in., $\alpha=0.548$, b=0.1 in. The vertical axis measures the cross sectional coordinate z. The horizontal axis measures $|\Phi|$ and $|\Psi|$, respectively, on different scales, with the maximum in each wave denoted by the number listed. This figure should be viewed together with Fig. 3, which shows the disposition of the incident and reflected beam axes.

Parametrization of scattering from weak bonding flaw in a two-layer Aluminum Plate



Debonding stiffness profile:

$$K = K_0 \exp\left[-\ln 0.05 \left(\frac{x-x_f}{l}\right)^2 \right]$$

Scattered field behaves like Gaussian beam

Fig. 4a

Horizontal displacements on top surface

$|u^i|$ = input beam
$|u^{sc}|$ = flaw scattered field
$|u|$ = total field

Scattered precursor (SC) is clearly visible

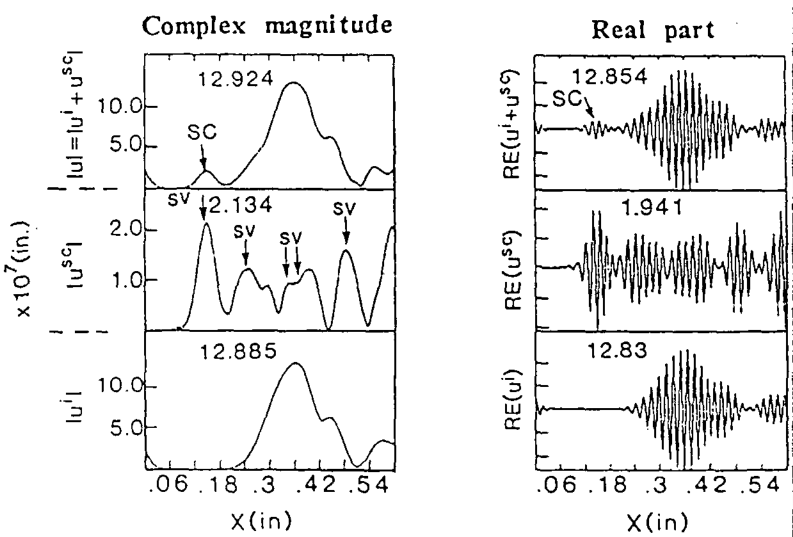
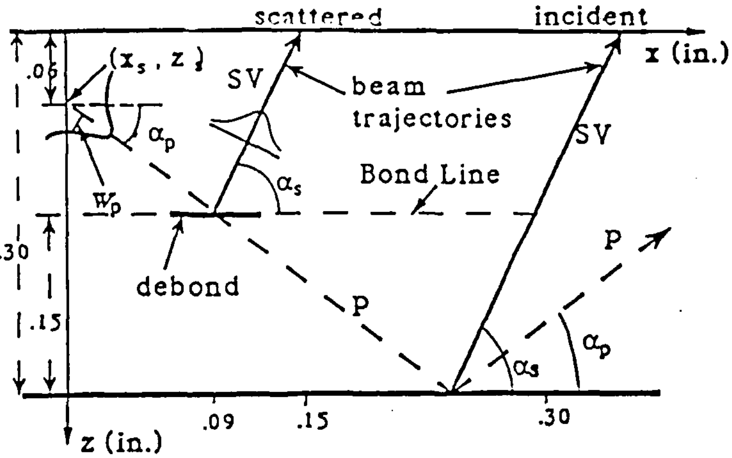


Fig. 4b

Test Problem: Two-layer Aluminum Plate with Weak Debond

I. Forward problem: Horizontal displacements u on upper plate

2-dim. Gaussian P-beam input
f=20 MHz
Beam waist :
w_p=.0335"
α_p =45^0
(x_s,z_s)=(0",.06")



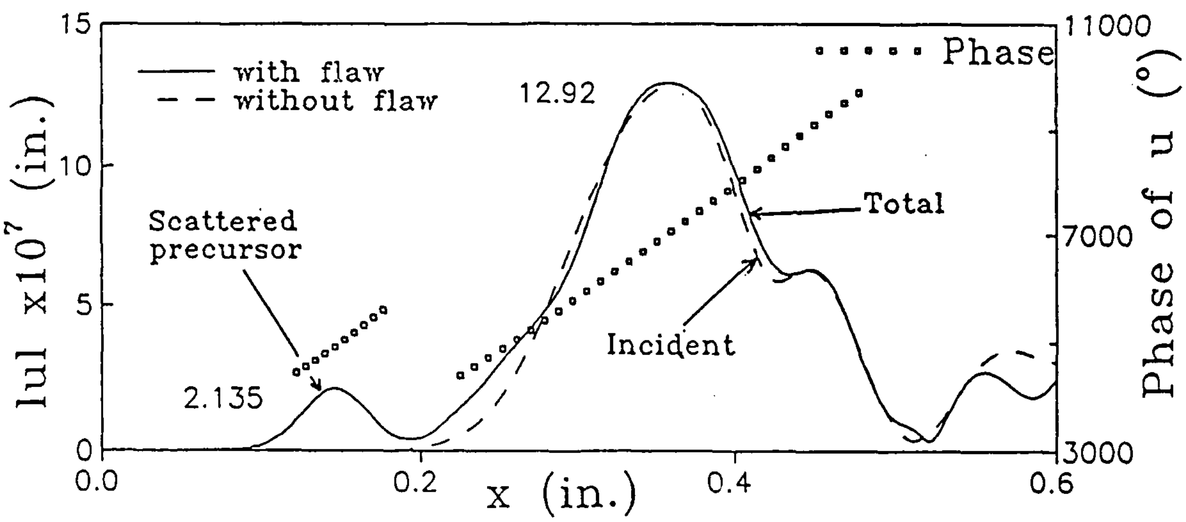
Aluminum plate
Thickness: a=.3"
Propagation speeds:
$v_s=1.209\times10^5$ in./sec
$v_p=2.36\times10^5$ in./sec
Density:
$\rho=2.53\times10^{-4}$ lb-sec^2/in
Subscripts:
p: comp.(P) wave
s: shear (SV) wave

Weak Debond

Gaussian pliability profile: $1/K(x,z_f) = (1/K_0)\exp\left(-[(x-x_f)/w_K]^2\right)$

$1/K_0 = (1/5.000\times10^9 \text{ lb/in}^3)$, $\quad w_K = .026"$

Synthetic reference ("measured") data



Beam Parametrization

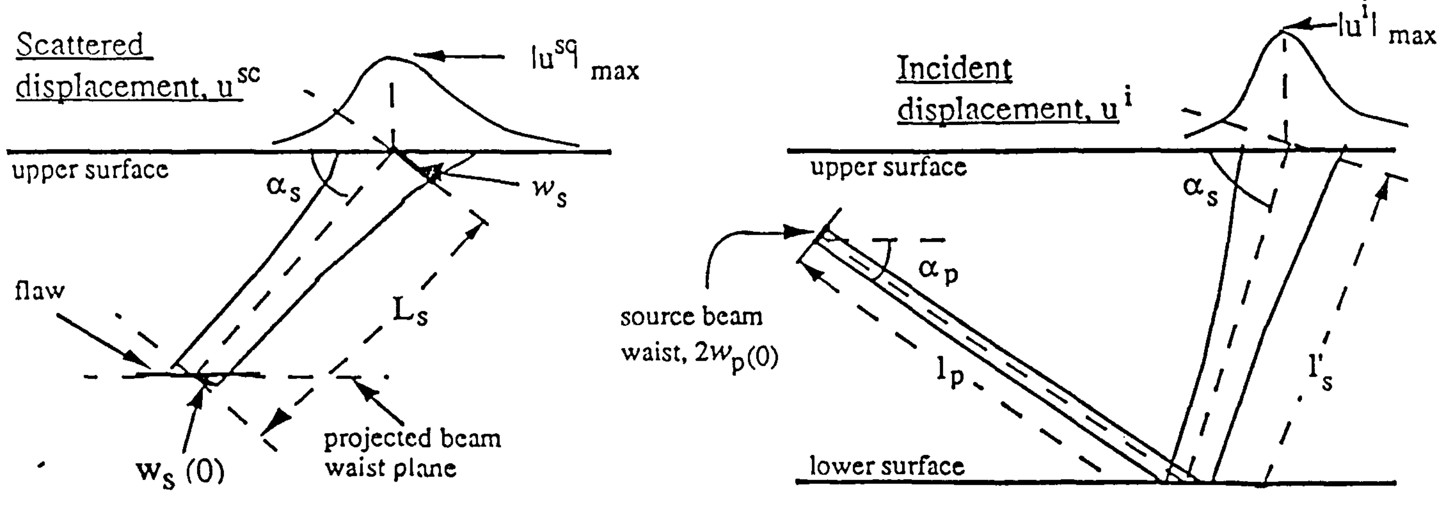


Fig. 5a

II. Inverse problem: Flaw reconstruction

A. Fit projected Gaussian wavefront to "measured" phase and amplitude data

B. Back-propagate precursor to waist plane: establishes flaw location

C. Back-propagate incid. portion to source, then forward-propagate to flaw: establishes flaw strength and width

Test Results for Pliability Profile

Flaw parameters	Original values	Reconstructed values
(x_f,z_f) (in.)	(.09,.15)	(.082,.168)
K_0 (lb/in.^{3})	5.000×10^9	5.002×10^9
w_K (in.)	.02599	.02565

$$1/K_0 = |\Delta u|_{max} / |\tau_{zx}|_{max}, \qquad \tau_{zx} = \text{tangential stress}$$

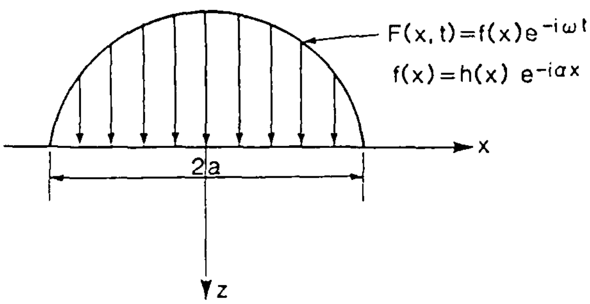
III. Conclusion

- Beam parametrization furnishes promising algorithm for detecting, locating and identifying strength of weak debonds of moderate extent
- Extension to three-dimensions, non-Gaussian inputs, and nonplanar plates is planned

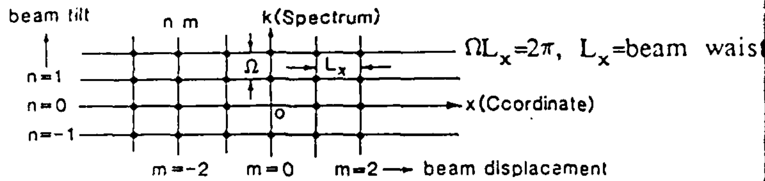
Fig. 5b

Transducer output modeling by Gaussians on a self-consistent (coordinate)-(spectrum) lattice

Aperture distribution



Beam lattice decomposition



$$f(x)=\sum_n\sum_m A_{mn}w(x-mL_x)\,e^{in\Omega x}$$

$$w(x)=\left(\frac{\sqrt{2}}{L_x}\right)^{\frac{1}{2}}\exp(-\pi x^2/L_x^2)\quad,\quad \int|w(x)|^2dx=1$$

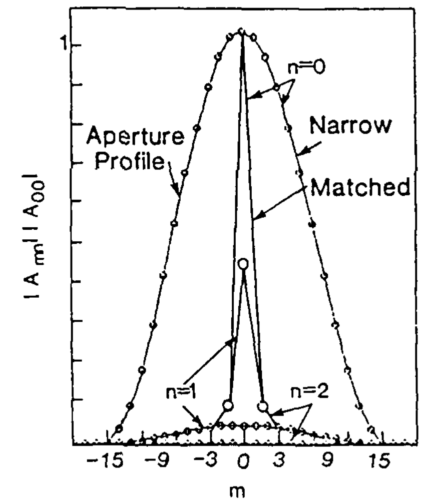
Fig. 6a

Transducer output modeling: (cosine)^2 distribution

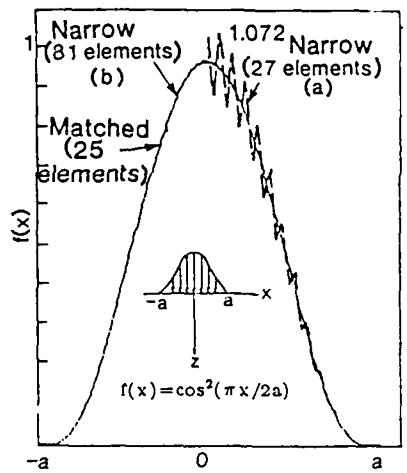
a) Aperture profile reconstruction:

$2a = 5\lambda_p$ (aperture width)

$$L_x = \begin{cases}(2a)/25 & \text{(narrow beams)}\\ 2a & \text{(matched beams)}\end{cases}$$



Gaussian amplitude coefficients

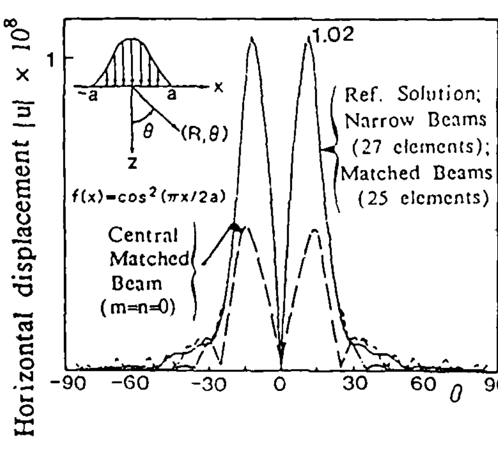


Field Synthesis

Narrow beams: along n=0 line

Matched beams: around m=n=0 (central beam)

b) Near field ($R=10\,\lambda_p$) radiation pattern



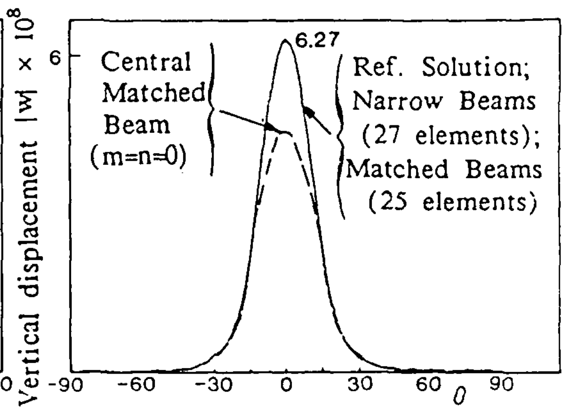


Fig. 6b